LF RFID Chequered Loop Antenna for pebbles on the beach detection

A. Diet, Y. Le Bihan, C. Conessa, F. Alves
GEEPS (PIEM) UMR 8507, Univ. Paris Saclay
F. 91192 Gif sur Yvette, France
antoine.diet@u-psud.fr

M. Grzeskowiak, M. Benamara, G. Lissorgues
ESYCOM EA 2552 (UPEMLV, ESIEE-Paris, CNAM)
Cite Descartes, BP99, 93162 Noisy le Grand, France
Cite Descartes, F. 77454 Marne-la-Vallée, France

M. Biancheri-Astier
GEOPS/GPIS UMR 8148, Univ. Paris-Saclay,
91405 Orsay, France

A. Pozzebon
University of Siena, Department of Information Engineering and Mathematical Sciences,
Via Roma 56, 53100 Siena, Italy

***Abstract*—This paper focus on low frequency (125 kHz) RFID by magnetic coupling, more precisely using *glasstag* type of tags in the context of pebble detection on the beach. The challenge is to detect over a wide area very small size tags which are highly sensitive to the orientation of the magnetic field. To improve the detection ability of the reader loop antenna, the paper proposes to exploit the principle of complementary loops. Theoretical simulations with MATLAB show the potential increase by means of mutual inductance value along a displacement of the tag. A prototype of a chequered loop structure is presented and tested with a classical low power RFID reader to demonstrate the improvement without increasing the current in LF reader loops. The detection performances reach 12,8% for a 900 cm² surface of a prototype reader loop, whatever the orientation of the *glasstag*.**

Keywords — LF RFID ; magnetic coupling

I. Detection of pebbles with LF RFID

Radio Frequency IDentification (RFID) is used in numerous applications domains (logistic, security, traceability of devices or persons…) by means of different realization technologies [1][2]. The frequency of operation, between the RFID reader/interrogator and the transponders (tags), is the discriminant factor due to multiple tradeoffs mainly concerning the detection range, data rate transfer and sensitivity to the environment (water, metal…). The RFID frequency of operation determines the electromagnetic phenomenon in near-field (magnetic coupling) or far-field (backscattering of radiating waves) used for data transfer.

Herein, we focus on the Low Frequency band, LF (125/134 kHz), in which the communication between the tag and the reader is achieved by load modulation, i. e. based on coils/loops magnetic coupling. In LF, most of the tags does not have battery and need being powered by magnetic coupling before being able to communicate. In a second step, the tag switches its load impedance to provide amplitude modulated information towards the reader. This type of LF RFID tags, often named as passive tags, should be powered efficiently by magnetic coupling but needs a sufficient bandwidth to transfer the data towards the reader. Consequently, a tradeoff is present on the quality factor of the transfer function between the tag and the reader, which is based on the impedance value seen by the reader, including the mutual inductance [1][2][3]. This mutual inductance can be defined by the Neumann formula (1) where $\boldsymbol{M}$ is the value, in Henry, between two closed paths $\boldsymbol{\Gamma_1}$ and $\boldsymbol{\Gamma_2}$ where r_{12} is the distance between the two elementary vectors $\boldsymbol{dl_1}$ and $\boldsymbol{dl_2}$. As it can be seen in (1), the mutual inductance is exclusively based on geometrical considerations: the position and orientation of the paths (loops in classical examples).

$$M = \frac{\mu_0}{4\pi} \oint_{\Gamma_1} \oint_{\Gamma_2} \frac{\overrightarrow{dl_1} . \overrightarrow{dl_2}}{r_{12}} \qquad (1)$$

RFID in LF (125/134 kHz) and HF (13,56 MHz) is widely used for traceability of animals (implanted tags for dogs, cats and fishes) or tracking of pebbles [4]. The LF is particularly used in presence of water (or/and metal) because the perturbation of such elements is proportional to the frequency.

As a consequence, LF RFID tags are dedicated technology for the study of coastal morpho-dynamics, in that it can be efficiently used to track the movements of sediments on coarse grained beaches, for both the under and outside sections of a beach. LF RFID tags can be embedded inside autochthonous pebbles turning them into tracers that can be positioned directly on the beach. These tracers can be then detected, identified and possibly recovered to study their movements and variations in terms of size and shape. These data are fundamental to evaluate the effects of coastal erosion on a beach and to plan the countermeasures to be deployed [4]. LF is the only frequency band that can be employed in such a scenario in that is the only one that is able to provide a Long Range communication channel even under sea water, allowing the detection of Smart Pebbles also in the submerged portion of a beach. Experimental tests with off-the-shelf devices have proven that 60cm communication ranges can be achieved if choosing specific types of tags [5][6] with high power RFID reader (>1W) and classical single turn wide loop (almost 50 cm of diameter).

Tags on pebbles has a minimum volume and the dedicated structure is a *glasstag* type which is typically made of a 1-1,5 cm long ferrite rod, with diameter in the range of 1-2 mm with enameled copper wire soldered to a RFID chip, as seen in Figure 1. Moreover, the penalty of the *glasstag* is it high sensitivity to the orientation because the ferrite rod is equivalent to a magnetic dipole with a very small effective surface due to the rod diameter value. As the pebbles can be positioned randomly, the RFID reader loop antenna is supposed to detect them whatever their orientation. This is technologically challenging because of the *glasstag* (high) sensitivity to the magnetic field orientation.

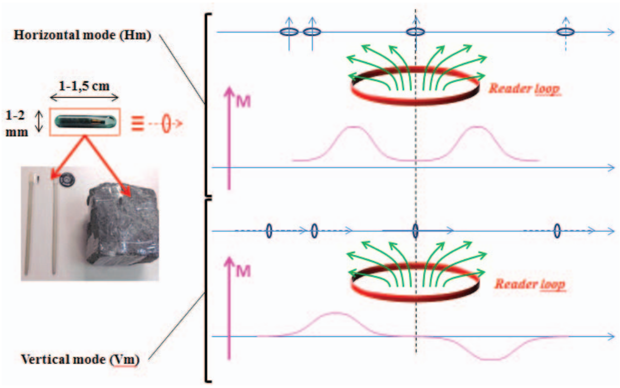

Figure 1: glasstag on pebbles (top left) and (right) parallel and vertical modes with mutual inductance when tag surface is small

As it can be seen in Figure 1, the horizontal and vertical modes for RFID detection create optimum cases near the edges of the reader loop. The horizontal mode does not present a maximum at the center (coaxial case for the reader and tag loops) in this Figure 1 because **we suppose in the described context that the reader loop size is higher than the tag loop size**. To overcome this penalty when using *glasstags* with wide reader loop, one can increase the current or modify the geometry of the reader loop [7][8][9] in order to increase the value of M, given by (1) and (2).

$$
\begin{aligned}
M &= \frac{\mu_0}{4\pi}\oint_{\Gamma_1=\Gamma_1^a+\Gamma_1^b}\oint_{\Gamma_2}\frac{\overrightarrow{dl_1}.\overrightarrow{dl_2}}{r_{12}} \\
&= \frac{\mu_0}{4\pi}\left[\oint_{\Gamma_1^a}\oint_{\Gamma_2}\frac{\overrightarrow{dl_1}.\overrightarrow{dl_2}}{r_{12}}+\oint_{\Gamma_1^b}\oint_{\Gamma_2}\frac{\overrightarrow{dl_1}.\overrightarrow{dl_2}}{r_{12}}\right] \\
&= M_a + M_b
\end{aligned}
\qquad (2)
$$

As expressed in (2) one idea is to separate the reader loop path defined by $\boldsymbol{\Gamma_1}$ into loop sub-paths (multi-loop or series loops) $\boldsymbol{\Gamma_1^a}$ and $\boldsymbol{\Gamma_1^b}$ which will drive to the addition of the two partial mutual inductances parts, one of which being potentially better suited for mutual coupling with the given geometry of the *glasstag*. This would improve the reader loop antenna structure before increasing the current, as is the classical solution proposed. As the pebbles are in the range of several centimeters, the spatial resolution is approximated to be 10x10 cm².

The idea in that paper is to improve the structure of the reader loop by modifying the ability (capacity) of mutual coupling in the case of a *glasstag*. The multi-loop principle is explored in that way.

Additionally, the ability to detect in both horizontal and vertical modes is more useful in the case of pebbles detection than to increase the detection range in only one mode.

II. Theoretical Approach

To improve the detection of LF RFID *glasstag*, we investigated three different solutions for a given area of 10x20 cm², as shown in Figure 2. The first solution (case "a") is a wide loop corresponding to current commercial reference solutions. The second and third cases are two serial loops of 10x10 cm², covering the same total area as the first loop, and for which the current is in phase (case "b") or out of phase (case "c"). The loops of case "c" are also named complementary loops [9][10][11].

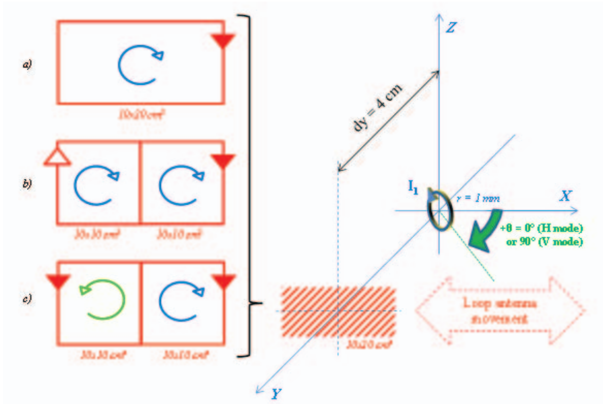

Figure 2: Reader loop area and glasstag equivalent magnetic dipole. Representation (left) of the three different studied solutions.

To compare the detection ability of such solutions described in Figure 2, we compute under MATLAB the evaluation of the mutual inductance "M". This value correspond to the flux induced from the reader loop onto the magnetic dipole surface, but also to the reciprocal flux induced by an equivalent magnetic dipole source onto the reader loop surface. Consequently, M is computed by means of the discrete orientated surface integral of the magnetic field generated by a turn of 2 mm equivalent diameter, with a spatial step of 5 mm², at a fixed distance of 4 cm on the Y axis, see Figure 2. The magnetic field is computed with (3).

$$
\left\{
\begin{aligned}
B_r &= \frac{I\mu_0 y}{2\pi\left[(R+r)^2+y^2\right]^{1/2} r}\left[\frac{R^2+r^2+y^2}{(R-r)^2+y^2}E(k)-K(k)\right] \\
B_\theta &= 0 \\
B_y &= \frac{I\mu_0}{2\pi\left[(R+r)^2+y^2\right]^{1/2} r}\left[\frac{R^2-r^2-y^2}{(R-r)^2+y^2}E(k)-K(k)\right] \\
k^2 &= \frac{4Rr}{(R+r)^2+y^2}
\end{aligned}
\right\}
\qquad (3)
$$

The results of the evaluation of M are presented in Figure 3 and, respectively, Figure 4 in function of the *glasstag* movement along the axis parallel to the reader loop surface ("X" axis in Figure 2), for horizontal and, respectively, vertical modes.

As the goal is to detect the tag whatever its orientation during a studied movement, we propose a figure of merit called Coupling Capacity (CC) by means of the integral of M(x) absolute value along the X axis, from -20 cm to +20 cm to include two times the length of the reference reader loop surface. This criterion, defined by (4), uses the absolute value of M because the powering of the tag is proportional to M².

$$CC_{tag} = \int_{X_1}^{X_2} \left| M_{tag}(x) \right| dx \tag{4}$$

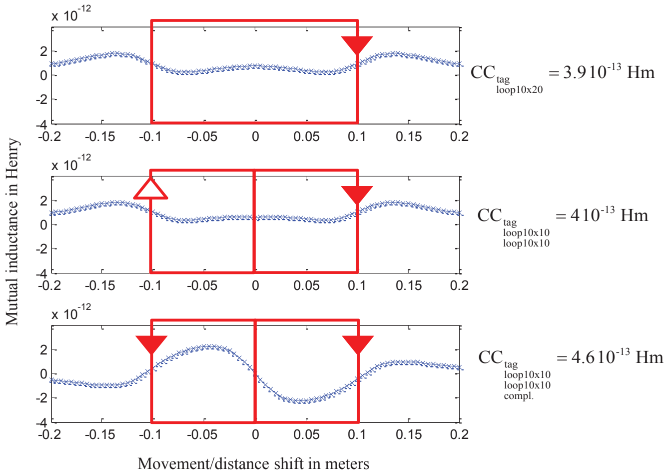

Figure 3: Magnetic coupling for the different solutions of reader loops structures, in function of the tag movement (X axis) in horizontal mode

As it can be seen in Figure 3 for the horizontal mode, the complementary loops (case “c”) provides higher maximum values of |M| than cases “a” and “b”, and presents also a stronger convexity of the curve M(x). It has to be noticed that the tag could not be detected at the center of the loop for case “c”, unlike for cases a) and b), due to the magnetic field distribution of the complementary loops.

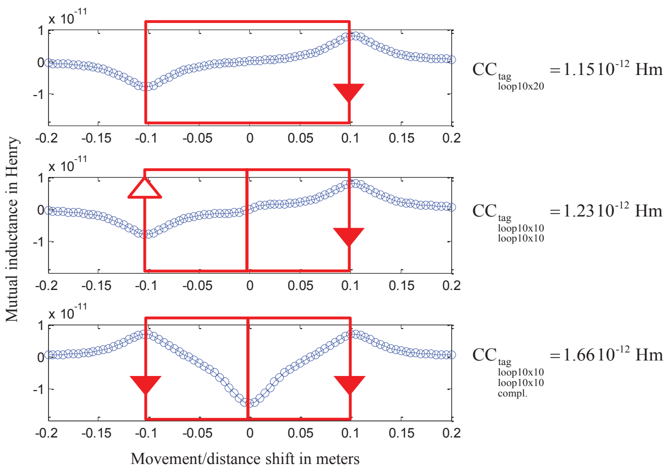

Figure 4: Magnetic coupling for the different solutions of reader loops structures, in function of the tag movement (X axis) in vertical mode

Results of M in the vertical mode are shown in Figure 4 and show a high similarity for case “a” and “b”. This is due to the fact that, in the case “b”, the loops currents along the common side are in opposite phase. In case “c” the loops currents along the current axis are in phase and, consequently, generate a strong magnetic field driving to a maximum value of |M| at the position X=0. Complementary loops of case “c” present an additional maximum for |M(x)| compared to cases “a” and “b”.

Additionally, the values of CC in the horizontal (see Figure 3) and vertical (see Figure 4) modes drive to the conclusion of a better capacity of the *glasstag* detection in the case “c”.

To conclude, the complementary loops structure is theoretically a better solution to improve the total surface of detection whatever the *glasstag* orientation because it provides the highest CC value for both modes.

III. PRACTICAL TESTS WITH LF RFID GLASSTAGS

The theoretical part emphasizes the advantage of complementary loops for LF RFID *glasstag* detection. In this part, we prototype the chosen structure for a wide area and use the loops with a commercial reader (Ib technology [12]) to perform detection tests. As the pebbles need not a resolution less than 10 cm, we build the structure with complementary square loops of 10x10 cm², as studied in the theoretical part. The enameled copper wire used for the loops has a diameter of 0.015 mm and a serial loss resistance which limit the surface. We set a total surface of 30x30 cm² in this paper because too high losses can prevent the detection. This matrix of 9 complementary squares loops is called the chequered loop antenna because it corresponds to an alternating distribution of the loops, in series, in function of the current phases, as seen qualitatively in Figure 5.

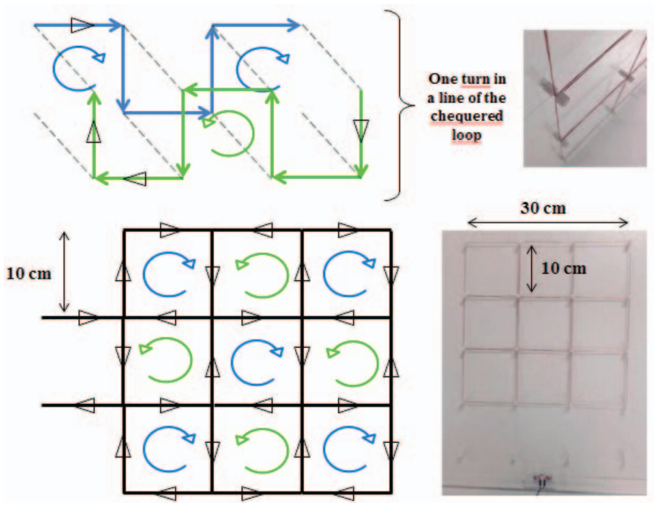

Figure 5: (top) Twisting of the wire to build the chequered loop lines. Representation of the current phases (bottom left) corresponding to the complementary loops principle. Chequered loop (bottom right)

The chequered loop antenna is realized with enameled copper wire fixed on a plexiglas board (0.5 cm thickness + 0.5 cm nylon spacer) and we test the RFID LF tags with HITAG S *glasstag* and the commercial reader from Ib technology. The chequered loop has a measured inductance of 820 µH (Q=12). The setup is shown in Figure 6 in which the pebble and the tag position are noticed. The RFID reader board is a low power (less than 1W) reader and the dedicated loop used for LF *glasstag* is typically a multi-turn loop of 10 cm diameter (can be seen in Figure 6 near the reader board) for which the detection range is about 4 cm. As the pebble is placed on the plexiglas, the detection range tested is at least at 1 cm.

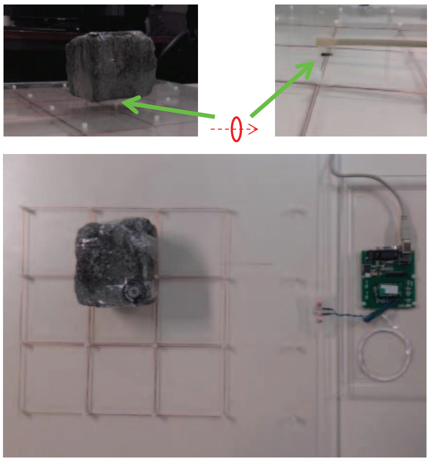

Figure 6 : RFID detection tests setup and a position where the glasstag is detected in vertical mode at 1 cm height.

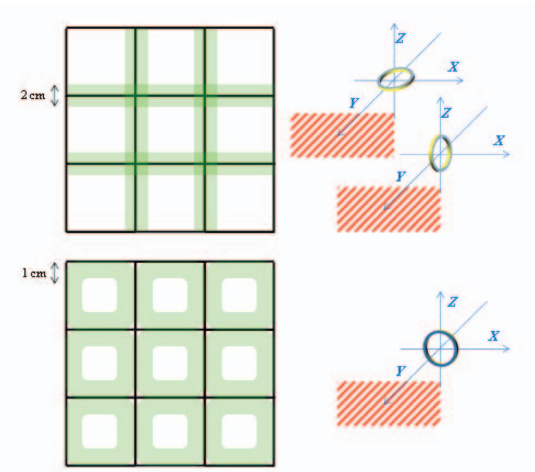

Figure 7 : RFID Detection area at a distance of 1 cm (at least) in vertical (top) and horizontal (bottom) modes

In Figure 7, the detection areas are qualitatively presented for multiple positions of the pebbles in horizontal and vertical modes. For such difficult cases of mutual coupling with a *glasstag* (very small equivalent surface of the magnetic dipole) the total detection area is made of the sum of each green areas represented in Figure 7, that is 2x30x4-2x2x4 = 224 cm² for the vertical mode (24,8%) and 9x(10²-9²) = 171 cm² for the horizontal mode (19%). An interesting aspect of these areas are their repartition, almost uniform, along the overall surface which make possible the potential detection of a moving glasstag (displacement and random orientation). If we define the intersection of the two detection surfaces in Figure 7, we have a total of 1x30x4-1x1x4 = 116 cm² (12,8%) which correspond to an area where the *glasstags* are detected whatever the mode, i. e. whatever their orientation.

IV. Conclusion and Perspectives

RFID LF pebble detection over a wide area is a very difficult challenge because the mutual coupling is very low due to the size of a *glasstag* effective surface. To overcome this problem, the typical solution is to increase the current and to use wider single turn loop antenna.

Another solution was proposed in this paper by means of a strong geometrical modification of the reader loop structure itself. The theoretical simulations showed that complementary loops are fruitful when trying to improve the mutual coupling for a given area of detection. Without increasing the current, a prototype for LF RFID *glasstags* detection is tested and showed that this chequered loop antenna has a total area of detection of 224+171 cm² for the horizontal and vertical modes of tag detection.

As the two modes are detected, the ability to detect a moving tag with a randomized orientation is possible without necessarily increasing the current.

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